Risk, Arbitrage, and Spatial Price Relationships: Insights from China’s Hog Market under the African Swine Fever

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Motivation

• Spatial market integration occurs when all arbitrage opportunities are exhausted and the spatial market achieves Pareto efficiency (Barrett and Li, 2006)
  • A rich literature testing for market integration using time series data (e.g., Ravallion, 1986; Shiue and Keller, 2007)

• Lacking careful examination of dynamic spatial relationships of prices as the integration is being formed
  • Fundamental to how commodity demand and supply shocks spread over time and space

• Limited causal exploration for spatial market (dis)integration
  • Consumer preferences, producer risk attitudes, and political barriers may drive the integration (Fan, 2002; Goyat, 2011; Ruan et al, 2021)
A Natural Experiment

- The 2018 outbreak of African Swine Fever (ASF) in China helps study spatial dynamics during the (re-)establishment of market integration

- China had a highly integrated hog market prior to ASF shock

- A temporary ban on inter-province shipment of live hogs was imposed to stop the spread of ASF

- The ban broke the initial integration, resulting in considerable, temporary spatial price divergence

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Research Question and Approach

• We examine and identify driving forces of spatial re-integration, after the shipping ban was lifted

• Use unique data of week-province specific hog prices from January 2016 to November 2020

• Our empirical strategy is multi-faceted
  • A innovative, generalized spatial model based on panel data to estimation spatial price links
  • Reduced-form tests to find determinants of price links
Findings

• Prior to the shipping ban, geographic distances between provinces do not weaken inter-province price links

• Longer distances become a significant obstacle to price linkage post the ban; faster re-integration in hog prices between proximate provinces

• The negative effect of inter-province distances can be rationalized by a conceptual model of arbitrage under risks and imperfect information

• The findings highlight the value of providing transparent public information in enhancing market integration and efficiency of domestic trade

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Roadmap

• China’s Hog Market
• African Swine Fever and Policies
• Conceptual Model
• Empirical Strategy
• Outcomes and Discussion
China’s Hog Market

• China is the world’s largest producer and consumer of hogs/pork
  • 500-600 million hogs are produced and consumed per year
  • Large producer provinces are not always large consumer provinces
  • Consumer preferences for “fresh” pork

Delgado, Ma, and Wang (2021)
2017 Hog Outputs across Provinces (mil head)
China’s Hog Market

- China is the world’s largest producer and consumer of hogs/pork
  - 500-600 million hogs are produced and consumed per year
  - Large producer provinces are not always large consumer provinces
  - Consumer preferences for “fresh” pork

- Large numbers of live hogs are transported across provinces, predominantly using open-air, trailer-trucks
  - Large numbers of small/medium-sized hog farms and slaughter plants trade with each other

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2017 Hog Net Imports across Provinces (10,000 MT)

Delgado, Ma, and Wang (2021)
ASF Outbreak in China

• ASF is a highly contagious animal disease which is spread via the ASF virus
  • Infection through infected hogs, leeches, birds, mice, and contaminated water/feed
  • The virus is able to stay alive in the air for days and remain active in blood/organs/droppings

• ASF was first found in NE China early August 2018

• ASF caused losses of tens of millions of hogs in the next two years
  • Hogs died of ASF or were culled by the government (Ma et al., forthcoming)
The Shipping Ban

• Virus may spread through inter-province shipment of hogs
  • Trucks from various locations meet at a slaughter plant and may spread the virus to each other if ≥1 trucks carry the virus
  • Animal inspection stations on inter-province highways may spread virus among trucks

• Starting from late August 2018, provinces gradually banned shipping live hogs from an “infected province” to other provinces
  • An infected province is one with >2 infected counties or neighbor with an infected province

• By December, all mainland provinces except for Hainan, imposed the ban
  • By mid-March 2019, almost all of the bans were lifted
  • Since then, the ban was occasionally imposed on specific counties where ASF was identified, but not at the province level

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Price Divergence Caused by the Ban
Explaining the Slow Re-Integration

• The substantial divergence in provincial-level prices implies obvious arbitrage opportunities across provinces, after the ban was lifted

• The divergence endured for over a year after the shipping ban was removed

• To explain in theory, we build a model of cross-provincial arbitrage under imperfect information on ASF
Imperfect Public Information on ASF

- Continuing price increases post the ban implies continuing supply reductions
- Officially reported number of cases and losses were likely to be far below the actual number of cases and losses
- From 2018 to 2019, the number of officially confirmed cases is 144 and the number of infected hogs is ~2 million
- But the actual reduction in hog supply was ~100 million head comparing 2019 output to 2018
Model Setup

• In week $t$, a hog farmer in province $i$ sells to a slaughter in province $j$, taking province-level prices as given
  • Home province price is $p_{it}$, and the price in the other province is $p_{jt}$
  • $\delta_{ijt} = p_{jt} - p_{it}$ net transportation costs and is positive

• Quantity of hogs for the farm is pre-determined at $q_t$

• Tradeoff between exploiting price wedges across provinces and catching the virus, when public information of ASF is imperfect

• If not infected, gain $\delta_{ijt}q_t$; if infected by ASF, lose $p_{it}q_t$
Arbitrage Decision

- Expected return from arbitrage is $\Delta E(\pi_{ijt}) = q_t [p_{jt}(1 - \theta_{ij}) - p_{it}]$
  - $\theta_{ij}$ is the probability of catching ASF in shipping hogs from province $i$ to province $j$
  - The expected return decreases in $\theta_{ij}$

- $\theta_{ij}$ increases in the distance between the two provinces
  - Longer distance, less private information, less accuracy of ASF information in province $j$
  - Longer distance, more stations, and higher probability of catching the virus during truck shipments (e.g., $\theta_{ij} = 1 - (1 - \theta)^K$)

- Hypothesis: arbitrage opportunity is less exploited as the inter-province distance increases in the post-ban periods
A Regional Policy

• In January 2019, a special region-level ASF policy was initiated by the central government.

• Six southern provinces formed a co-managing agency to conduct actions over ASF and other animal diseases and share information.

• Hypothesis: the distance matters less for provinces in the South region in the post-ban periods.

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Panel Data of Hog Prices

- A balanced panel dataset of weekly province-level hog prices from Jan 1, 2016 to Nov 10, 2020
  - 252 weeks and 29 provinces (2 mainland provinces excluded due to missing data)
  - Four periods: pre-ban, ban, post ban 1, and post ban 2

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Province hog price in Period 1</td>
<td>15.81</td>
<td>0.34</td>
<td>15.11</td>
<td>16.69</td>
<td>RMB/kg</td>
</tr>
<tr>
<td>Province hog price in Period 2</td>
<td>13.05</td>
<td>1.56</td>
<td>10.45</td>
<td>16.71</td>
<td>RMB/kg</td>
</tr>
<tr>
<td>Province hog price in Period 3</td>
<td>24.56</td>
<td>1.53</td>
<td>20.98</td>
<td>27.04</td>
<td>RMB/kg</td>
</tr>
<tr>
<td>Province hog price in Period 4</td>
<td>31.71</td>
<td>1.59</td>
<td>28.79</td>
<td>35.73</td>
<td>RMB/kg</td>
</tr>
</tbody>
</table>
Spatial Model

- Given the panel dataset, our first goal is to characterize the spatial price relationships among the 29 provinces
  - Estimate inter-province price links using a spatial model

- In the traditional spatial model, the elements of spatial matrix follow a pre-specified spatial structure
  - E.g., geographic distances between provinces
  - Geographic distances may not be good basis for price links in the hog market
  - Complex spatial price relationships driven by factors other than the distance

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Spatial Model

• de Paula et al. (2018) develop a generalized spatial model
  • No pre-specified spatial structure, but allowing for data-driven spatial links
  • Take care of multivariate spatial connectivity
  • Estimated using a high-dimensional GMM method (adaptive elastic net GMM)

• The pre-determined spatial model is a special case of this new model

• Estimated inter-province price links allow us to further explore various determinants in each period of interest
  • Not possible in the traditional model where links are postulated
Spatial Model Setup

• A panel-data spatial model:

\[ p_{itm}^m - \overline{p}_{tm}^m = \rho^m \sum_{j=1}^{29} w_{ij}^m (p_{jtm}^m - \overline{p}_{tm}^m) + v_i^m + \mu_t^m + \epsilon_{itm}^m \]

• \( m \in \{1,2,3,4\} \) denotes the four periods, each covering \( i = 1,2,\ldots,29 \) provinces

• \( t_m = 1,2,\ldots,T_m \) weeks per period

• \( p_{itm}^m \) is period-specific price of province \( i \), and \( \overline{p}_{tm}^m \) is the average price in that period

• \( \sum_{j=1}^{29} w_{ij}^m (p_{jtm}^m - \overline{p}_{tm}^m) \) is the spatial lag of prices

• \( w_{ij}^m \in (0,1) \) is the inter-province price link, \( v_i^m \) province FE, and \( \mu_t^m \) month FE

• Choose initial values based on AIC

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Inter-Province Distance

• Consider two measurements of the inter-province distance

• First, $D_{ij}$ is the geographical distance between province capital cities
  • Unit: 1000 kilometers

• Second, $D_{ij}$ is the geographical “economic” distance between provinces
  • Use 2016 price wedges among provinces as a proxy
  • Take the mean price wedge as the average cost of arbitrage between two provinces, given that most province pairs are co-integrated in the pre-ASF period
  • Unit: real 2018 RMB/kilogram
Price Links and Distances

Table 2. Summary Statistics of Estimated Spatial Matrices and Distances

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated $w_{ij}$ in Period 1</td>
<td>0.16</td>
<td>0.14</td>
<td>0.00</td>
<td>0.98</td>
<td>-</td>
</tr>
<tr>
<td>Estimated $w_{ij}$ in Period 2</td>
<td>0.27</td>
<td>0.25</td>
<td>0.00</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>Estimated $w_{ij}$ in Period 3</td>
<td>0.51</td>
<td>0.31</td>
<td>0.00</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>Estimated $w_{ij}$ in Period 4</td>
<td>0.32</td>
<td>0.14</td>
<td>0.00</td>
<td>0.84</td>
<td>-</td>
</tr>
<tr>
<td>Geographic $D_{ij}$</td>
<td>1.31</td>
<td>0.70</td>
<td>0.11</td>
<td>3.46</td>
<td>1000km</td>
</tr>
<tr>
<td>Economic $D_{ij}$</td>
<td>0.56</td>
<td>0.24</td>
<td>0.11</td>
<td>1.57</td>
<td>Real 2018 RMB/kg</td>
</tr>
</tbody>
</table>

Source: Authors’ calculation. Notes: The number of observations is 812. Statistics are weighted by observations.
Additional Explanatory Variables

- We add a few other province-specific variables that help explain the variance in estimated price links
  - Hog outputs, net pork import, and weeks banned

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>SD</th>
<th>Min</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Province hog outputs</td>
<td>2.42</td>
<td>1.90</td>
<td>0.11</td>
<td>6.58</td>
<td>10 mil heads</td>
</tr>
<tr>
<td>Province importer (0,1 with 1=yes)</td>
<td>0.55</td>
<td>0.50</td>
<td>0.00</td>
<td>1.00</td>
<td>-</td>
</tr>
<tr>
<td>No. weeks province under ban</td>
<td>25.16</td>
<td>4.64</td>
<td>12</td>
<td>34</td>
<td>-</td>
</tr>
</tbody>
</table>
Reduced-Form Model

- Identify determinants of price links:
  \[ \ln \left( w_{ij}^m \right) = c + \alpha \ln(D_{ij}) + \beta \ln(\bar{p}_{jm}) + S_{ij} + \Gamma_{ij} + \Omega_{j} + F_{i} + e_{ij}^m \]
  - \( w_{ij}^m \) is the estimated period specific price link between provinces
  - \( D_{ij} \) is the distance between province capital cities
  - \( \bar{p}_{jm} \) is the period-specific average hog price in province \( j \)
  - \( \Gamma_{ij} \) is the number of weeks under the ban
  - \( S_{ij} \) is the south-south indicator for a pair of provinces
  - \( F_{i} \) is province FE, \( e_{ij}^m \) clustered at the province level

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Baseline Findings: Geographical Distance

<table>
<thead>
<tr>
<th></th>
<th>(1) Pre-ban</th>
<th>(2) Ban</th>
<th>(3) Post-ban 1</th>
<th>(4) Post-ban 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance between provinces i and j</td>
<td>0.08</td>
<td>0.07</td>
<td>-0.10*</td>
<td>-0.27***</td>
</tr>
<tr>
<td></td>
<td>(0.10)</td>
<td>(0.12)</td>
<td>(0.05)</td>
<td>(0.09)</td>
</tr>
<tr>
<td></td>
<td>[0.42]</td>
<td>[0.56]</td>
<td>[0.05]</td>
<td>[0.00]</td>
</tr>
<tr>
<td>#weeks under the ban</td>
<td>-0.02*</td>
<td>-0.02**</td>
<td>-0.01</td>
<td></td>
</tr>
<tr>
<td>provinces i and j</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.01)</td>
<td>(0.01)</td>
<td>(0.01)</td>
<td></td>
</tr>
<tr>
<td>South-south (1, yes)</td>
<td></td>
<td></td>
<td>0.40**</td>
<td>-0.04</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.15)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(0.10)</td>
</tr>
<tr>
<td>Province j average price in the period</td>
<td>6.29*</td>
<td>-1.27***</td>
<td>-1.29**</td>
<td>-0.98*</td>
</tr>
<tr>
<td></td>
<td>(3.16)</td>
<td>(0.45)</td>
<td>(0.51)</td>
<td>(0.57)</td>
</tr>
<tr>
<td>Pre-ban $\bar{w}_{ij}$</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Province j controls</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>Province i FE</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.57</td>
<td>0.48</td>
<td>0.64</td>
<td>0.36</td>
</tr>
<tr>
<td># observations</td>
<td>812</td>
<td>812</td>
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</tr>
</tbody>
</table>

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## Robustness Test 1: Additional FE

<table>
<thead>
<tr>
<th></th>
<th>(1) Pre-ban</th>
<th>(2) Ban</th>
<th>(3) Post-ban 1</th>
<th>(4) Post-ban 2</th>
<th>(5) Pre-ban</th>
<th>(6) Ban</th>
<th>(7) Post-ban 1</th>
<th>(8) Post-ban 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance between provinces (i) and (j)</strong></td>
<td>0.08 (0.10)</td>
<td>0.07 (0.12)</td>
<td>-0.10* (0.05)</td>
<td>-0.27*** (0.09)</td>
<td>0.09 (0.10)</td>
<td>-0.12 (0.09)</td>
<td>-0.19*** (0.06)</td>
<td>-0.26*** (0.08)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong># weeks under the ban provinces (i) and (j)</strong></td>
<td>-0.02* (0.01)</td>
<td>-0.02** (0.01)</td>
<td>-0.01 (0.01)</td>
<td>-0.03** (0.01)</td>
<td>-0.01*** (0.01)</td>
<td>-0.02 (0.01)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>South-south (1, yes)</strong></td>
<td>0.40** (0.15)</td>
<td>-0.04 (0.10)</td>
<td>(0.01)</td>
<td>(0.01)</td>
<td>(0.15)</td>
<td>(0.10)</td>
<td>0.15 (0.01)</td>
<td>-0.04 (0.12)</td>
</tr>
<tr>
<td><strong>Province (j) average price in the period</strong></td>
<td>6.29* (3.16)</td>
<td>-1.27*** (0.45)</td>
<td>-1.29** (0.51)</td>
<td>-0.98* (0.57)</td>
<td>(0.15)</td>
<td>(0.10)</td>
<td>(0.13)</td>
<td>(0.12)</td>
</tr>
<tr>
<td><strong>Pre-ban (w_{ij})</strong></td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Province (j) controls</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Province (i) FE</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>(R^2)</strong></td>
<td>0.57</td>
<td>0.48</td>
<td>0.64</td>
<td>0.36</td>
<td>0.59</td>
<td>0.60</td>
<td>0.67</td>
<td>0.42</td>
</tr>
<tr>
<td><strong># observations</strong></td>
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</tbody>
</table>

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## Robustness Test 2: Economic Distance

<table>
<thead>
<tr>
<th></th>
<th>(1) Pre-ban</th>
<th>(2) Ban</th>
<th>(3) Post-ban 1</th>
<th>(4) Post-ban 2</th>
<th>(5) Pre-ban</th>
<th>(6) Ban</th>
<th>(7) Post-ban 1</th>
<th>(8) Post-ban 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Distance between provinces i and j</strong></td>
<td>0.18 (0.14)</td>
<td>0.22 (0.14)</td>
<td>-0.09* (0.05)</td>
<td>-0.13 (0.08)</td>
<td>0.11 (0.16)</td>
<td>-0.17 (0.11)</td>
<td>-0.13** (0.06)</td>
<td>-0.10 (0.09)</td>
</tr>
<tr>
<td></td>
<td>0.19</td>
<td>0.27</td>
<td>-0.02*</td>
<td>-0.02**</td>
<td>-0.02*</td>
<td>-0.04***</td>
<td>-0.02***</td>
<td>-0.03*</td>
</tr>
<tr>
<td><strong>#weeks under the ban provinces i and j</strong></td>
<td>0.01 (0.01)</td>
<td>0.01 (0.01)</td>
<td>0.02 (0.01)</td>
<td>0.01 (0.01)</td>
<td>0.01 (0.01)</td>
<td>0.00 (0.00)</td>
<td>0.27 (0.02)</td>
<td>0.16 (0.02)</td>
</tr>
<tr>
<td><strong>South-south (1, yes)</strong></td>
<td>0.43** (0.17)</td>
<td>0.43** (0.17)</td>
<td>0.08 (0.09)</td>
<td>0.08 (0.09)</td>
<td>0.27 (0.02)</td>
<td>0.16 (0.02)</td>
<td>0.27 (0.18)</td>
<td>0.16 (0.10)</td>
</tr>
<tr>
<td><strong>Province j average price in the period</strong></td>
<td>5.05* (2.68)</td>
<td>-1.53** (0.55)</td>
<td>-1.15** (0.49)</td>
<td>-1.02 (0.80)</td>
<td>5.05* (2.68)</td>
<td>-1.53** (0.55)</td>
<td>-1.15** (0.49)</td>
<td>-1.02 (0.80)</td>
</tr>
<tr>
<td><strong>Pre-ban ( \omega_{ij} )</strong></td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Province j controls</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td><strong>Province i FE</strong></td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
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</tr>
<tr>
<td><strong>R^2</strong></td>
<td>0.57</td>
<td>0.48</td>
<td>0.64</td>
<td>0.36</td>
<td>0.59</td>
<td>0.60</td>
<td>0.66</td>
<td>0.41</td>
</tr>
<tr>
<td><strong># observations</strong></td>
<td>812</td>
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<td>812</td>
<td>812</td>
<td>812</td>
<td>812</td>
<td>812</td>
</tr>
</tbody>
</table>
Policy Implications

• Inconsistency between public and private information about ASF led to uncertainty for producers and processors and efficiency loss
  • Market re-integration began relatively early where information transparency was greater

• The government should strive to maintain certainty and transparency in information regarding the disease outbreak if it wants to maintain safe trade and efficient within the region

• Developing cold chain logistics may help mitigate the spread of animal epidemics in the future
  • Confined transportation and lower survival of virus
Further Discussion

• The value of providing high-quality public information applies to animal epidemics in general and to human epidemics involving travel within and across countries

• The generalized spatial model has broader applications
  • Used with regular panel data, no need for survey on network, etc.
  • Could be implemented in other context, including international trade and personal networks
References


Topics for Discussion

- Other drivers of integration?
- Measuring efficiency loss?
Officially Reported Cases across Provinces (2018-2020)
### Table A2. Correlation Coefficients of Key Variables

<table>
<thead>
<tr>
<th>Variables</th>
<th>Estimate $d w_{ij}$ in Period 1</th>
<th>Estimate $d w_{ij}$ in Period 2</th>
<th>Estimate $d w_{ij}$ in Period 3</th>
<th>Estimate $d w_{ij}$ in Period 4</th>
<th>Geog. $D_{ij}$</th>
<th>Econ. $D_{ij}$</th>
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<tr>
<td>Estimated $w_{ij}$ in</td>
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<tr>
<td>Period 1</td>
<td></td>
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<td>Period 3</td>
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<tr>
<td>Estimated $w_{ij}$ in</td>
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<td>0.09</td>
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<td>Period 4</td>
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<td>Geographic $D_{ij}$</td>
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<td>-0.01</td>
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<td>0.02</td>
<td>-0.16</td>
<td>0.54</td>
<td>1.00</td>
</tr>
</tbody>
</table>
Cointegration Tests \textit{(Periods 1 and 2)}

(a) Pre-ban period

(b) Ban period

Delgado, Ma, and Wang (2021)
Cointegration Tests (*Periods 3 and 4*)

Delgado, Ma, and Wang (2021)
Local Spatial Autocorrelation Clusters (Periods 1 and 2)
Local Spatial Autocorrelation Clusters (Periods 3 and 4)